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From theory to reality: The quest for gravitational waves

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Abstract. In 2015, the direct detection of the gravitational waves (GWs) produced by the acceleration of objects in spacetime verified one of the most significant predictions of the theory of general relativity (GR) raised by Albert Einstein almost a century ago. This detection was hailed as a century discovery and a perfect embrace of Einstein and GWs. Since then, gravitational-wave astronomy began to test the features of gravity, the characteristics of black holes, and GWs produced by two merging neutron stars were detected in 2017, which greatly pushed the development of astronomy. This article, beginning with the problems of Newtonian mechanics, reviews the process of Einstein's proposal of the special relativity theory and the formulation of the GR theory. It also covers how Einstein predicted the existence of GWs, the detection endeavours made by scientists, and how GWs were first directly detected 100 years after the prediction. It also presents the scientists' current efforts, envisions their future explorations in this field, and analyses the significance of detecting gravitational waves.

Keywords: Special Relativity Theory, General Relativity Theory, Einstein, Gravitational Waves.

1. Introduction

Einstein was born into a Jewish family in Germany in 1879 and remained unwilling to speak until the age of seven. At the age of ten, Einstein began to develop a strong interest in mathematics, physics, and philosophy, and to teach himself Euclidean laws of geometry. At the age of sixteen, he completed teaching himself calculus. Then in 1895 he was admitted by the Swiss Federal Institute of Technology.

In his "miracle year" of 1905, Einstein got his Ph.D. from the University of Zurich and proposed quantum theory and the photo quantum hypothesis, solving the problem of the photoelectric effect. Also in this year, Einstein proposed the principle of special relativity, demonstrated that space and time are not absolute [1]. In 1915, Einstein proposed the gravitational equation in generality relativity (GR) theory, which maintains that gravity causes a bending in space and time around huge objects. In 1916, he asserted that GWs would be created by the space-time rippling and would move away from the mass at the speed of light [2], and started to verify the existence of the predicted GWs. In 1936, Einstein submitted an article with his assistant Nathan Rosen, denying the existence of GWs. The review committee claimed that there was a mathematical mistake in his paper and the conclusion was incorrect. Later, Einstein, with the help of his colleagues, realized his own mistake and corrected it, and changed the title of his article to "On Gravitational Waves", thus admitted the existence of GWs again [3]. In February 2016, almost one hundred years after Einstein first predicted the existence of GWs, American scientists announced that the Laser Interferometric Gravity-wave Observatory (LIGO) located in Washington and Louisiana has successfully detected GWs, which caused a sensation in global scientific

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community. The media and scientific journals hailed this detection as a breakthrough of the century [4]. It is considered a watershed event [5], as it not only showed that humankind could directly detected GWs but also disclose new understandings about these extraterrestrial objects and the universe. This direct detection, followed by tens of other events, verified Einstein's GR theory.

This article probes into the process of Einstein's proposal of theory of special relativity and of GR, his prediction, and the direct detection of the GWs. It also presents scientists' current efforts, envisions their future explorations in this field, and analyses the significance of detecting GWs.

2. Einstein's special relativity theory

2.1. Problems of Newtonian mechanics

In 1687, Newton published "Mathematical Principles of Natural Philosophy", marking the establishment of classical mechanics, which for a long time became the Bible and authority in the minds of physicists. The core of Newton's classical mechanics is the Galilean transformation, which, in classical mechanics, is a technique for transforming between two reference frames that only move relative at a constant speed, and belongs to a type of dynamic transformation. The Galilean transformation constructed the spatiotemporal view of classical mechanics. Both time and space are independent of the motion state of the reference frame, and time and space are independent and absolute. This absolute view of time and space ensures that the laws of classical mechanics have the same form in the eyes of observers in different states of motion.

Influenced by classical mechanics, physicists believed that there was a substance called ether in the universe, and that ether was the medium for spreading light, and that gravity, even electricity and magnetism, would propagate within the ether, thus developing the "light ether" hypothesis. In addition, physicists have viewed the ubiquitous "ether" as an absolute inertial frame, and the vector superposition of the ether reference frame speed and the observer's reference frame speed determines the measured speed of light in other reference frames. Later, Maxwell's electromagnetic theory have taught people that light is a wave that propagates at a constant rate of 300000 km per second relative to the "ether", meaning that the absolute inertial frame of ether does not exist.

Albert Michelson, together with Morley, used his interferometer in 1887 to accurately compare the rates of beams in different directions. However, the results of the experiment showed that beams of light from different directions had the same velocity, and no measurements were made of the Earth's rate of speed through the ether. The negative results of this experiment seemed to indicate that the Earth's movement in relation to the 'ether' does not exist. People were deeply surprised and disappointed by this result, and several famous physicists attempted to explain it within the framework of classical spacetime views, but none of them succeeded. It was not until Albert Einstein advanced the theory of relativity in 1905 that this problem was fundamentally solved.

2.2. Lorentz transformations

Einstein formulated his theory partly based on the work of Lorentz, the mathematician and physicist who introduced the concept of local time to explain relative simultaneity in 1895 and worked on comparable transformations to explain why the Michelson-Morley experiment didn't produce a desired result. According to Lorentz, the length reduces in the direction of motion when the observer moves at a specific speed in relation to the ether, cancelling out the variations in light speed.

Lorentz published his coordinate transformations in 1899, and he incorporated time dilation into his theory in 1904. Henri Poincare revised the algebraic formulas in 1905 and gave them the name "Lorentz transformations". The transformations to some extent reconciled the contradiction between classical mechanics and electrodynamics, but in Lorentz theory, the quantities introduced by the transformation are only seen as mathematical aids and do not include the relativistic view of time and space. Lorentz proposed it to save the erroneous ether hypothesis and lacked the relativistic mind. It was Einstein who first interpreted the Lorentz transformations in the right way.

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2.3. Special relativity theory

Einstein believed that since the speed of light remained constant, ether needn't exist as a stationary reference frame. In 1905, he raised the theory of special relativity based on the principle of relativity and the principle of constancy of the speed of light [6]. Einstein's observation focused on modifying basic concepts such as motion, time, and space, rederiving the Lorentz transformation, and endowing it with new physical content to explain the Michelson-Morey experiment and the constancy of light's speed.

Special relativity, by using Lorentz transformations at high velocities, brings forth several consequences, including time dilation, velocity transformation and length contraction, etc. The theory of special relativity also led to one significant result, the so-called mass-energy relationship $E = mc^2$. When people use this relationship to explain mass loss, they discover that the atomic nucleus contains enormous energy, which was verified by the energy of mass released by the two atom bombs in Japan in 1945.

3. Einstein's GR theory

3.1. Raising GR theory

One problem with theory of special relativity is that it neglects the effect of gravity on the physics laws, including the laws of motion. Special relativity would be constant only for special cases like a non-accelerating frame or frame of reference. Hence, there is a need to propose a theory in which frame of reference changes with respect to other frames while considering the effect of gravity [7].

In 1905, Einstein wrote a paper that examined the impact of gravity and acceleration on light in special relativity. In 1908, Einstein asserted that a body falling freely in a vacuum would not experience any force, and therefore gravity was equivalent to acceleration [1]. This understanding finally evolved into the principle of equivalence, the core of GR theory. Its basic meaning is that the gravity field is equivalent to a reference frame moving at an appropriate acceleration.

In 1912, another paper was published by Einstein to explore how gravitational fields can be described in geometric way. It was not until 1915 when the Einstein field equations were published that GR was finally completed. In this theory, universe was depicted as a geometric system made up of three spatial dimensions and a time dimension. Mass, energy, and momentum caused the spacetime coordinate system to curvature, and gravity was moving along this curved spacetime.

Aside from the principle of equivalence, theory of relativity includes some other principles, like the general principle of relativity, the principle of general covariance, and the principle of spacetime curvature.

3.2. Proving the GR Theory

In 1919, British astronomer Eddington and Crommelin led teams to Spain and Brazil respectively to observe Mercury's perihelion and the curvature of light near the sun during solar eclipses, proving Einstein's ideas and calculations correct [8]. Einstein rose to fame among the public overnight. More subsequent tests proved the GR theory. In 1919, scientists observed gravitational deflection of starlight by the sun. In 1954, scientists observed the gravitational redshifts when doing the astronomical measurements, and in 1959 the redshifts were observed in laboratory [9]. In 1964, scientists observed the gravitational time delay.

4. Gravitational Waves

4.1. Detection of Gravitational Waves

In 1916, one year after Einstein raised GR, he made the prediction that gravitational radiation existed [10]. Since then, physicists around the world began working on this intriguing prediction.

The indirect proof of the existence of GWs came from Taylor and Hulse, who found the pulsed neutron binary in 1974 and conducted long-term observations of its orbital motion period. According to

GR, neutron binary systems emit GWs during orbital motion, resulting in smaller orbits and shorter periods. Hulse and Taylor's observations are in excellent agreement with GR and they won the 1993 Nobel Prize for this indirect verification of existence of GWs.

The direct detection of GW efforts by humans has a history of nearly 70 years. In 1969, Weber announced that he found GWs with his self-invented aluminum cylinder. However, no scientist could replicate his finding. However, his exploration attracted other researchers into studying gravitational waves. In the 1970s and 1980s, Pirani, Weber, and Weiss proposed the idea of using a laser interferometer to detect GWs. Two Laser Interferometer Gravitational Wave Observatory (LIGO) facilities, with arms of length of 4 kilometers arranged vertically, were built in Washington and Louisiana in 1999. Once GWs enter the earth, they cause spatiotemporal oscillations, leading to changes in the distance of the interference arm, which will give rise to changes in the interference fringes of the interferometer, thereby determining the strength of the gravitational wave. In 2010, the detectors, having made no findings, were shut down for upgrades. During this period, many laser interferometric GW detection stations have been built by Italy, Germany, United Kingdom, and Japan. These GW detectors have made significant progress in the detection of GWs, and become the mainstream equipment for gravitational wave detection.

A hugely upgraded LIGO, called Advanced LIGO, with a much stronger ability to search for GWs, began its first observing run in September 2015. Soon after its operation, the GW (with the detection code GW150914) was detected. Its signal, with a duration of about 200 milliseconds and an oscillation frequency of 30-150 Hz, came from the merger of two black holes which are 1.3 billion light years away from the Earth. The mass of two intertwining black holes was approximately equivalent to 30 suns, and they emitted GWs during the final destructive collision and merger. Three months later, a second GW GW151226 was directly detected by LIGO, and scientists could more accurately estimate the stellar black hole population and the constraints on possible GR deviations [10]. In August 2017, LIGO and Virgo worked together and detected GW170817 when two neutron stars merged. This was another important event which announced the debut of multi-messenger astronomy [1]. Five years since the first detection, more than 50 GWs emitted by neutron stars and black holes have been detected. These signals have deepened people's understanding about the formation of compact objects and their progenitor stars, tested GR, and revealed the behavior of matter at supranuclear densities [11].

4.2. Current Efforts of GW Detection

4.2.1. Ground-based detection stations. Current detectors on the ground use upgraded Michelson interferometry to identify GWs, covering the high frequency portion of the GW spectrum from ~10Hz to ~10 kHz to detect merging black holes, neutron stars, supernovae and isolate neutron stars.

To achieve the best effect, the globally distributed interferometers should establish a network to do the detection. Since 2015, LIGO and Virgo detectors have been highly coordinated in searching the GW in a series of observations. Recently, they welcomed a new member, Japan's 3-kilometere-armlength KAGRA detector, and formed the LIGO-Virgo-KAGRA network. Very soon, India's LIGO detector will also join the network. The two smaller detectors, 600-metre-armlength GEO600 and 300-metre-armlength Japanese TAMA, are used as back-up detectors and especially to test new measurements techniques for upgrading the more advanced detectors [11].

4.2.2. Space-based detection stations. In December 2015, European Space Agency launched the Laser Interferometer Space Antenna (LISA) Pathfinder spacecraft and operated it for two years to pave the way for the space-based GW interferometer LISA. LISA Pathfinder has contributed a lot to the LISA mission because it has found some key operation conditions needed by the forthcoming LISA mission.

LISA, to be launched in the mid-2030s, will cover the 100μHz to 100mHz frequency band. Lisa is composed of three satellites, and they form an equilateral triangle with 2.5 million kms on each side. Three detection arms, based on the tiny time difference of the GWs detected on each side, can calculate the direction of the event through triangular positioning. The distance of the event can be calculated from the size of the gravitational wave, and the energy and mass of events can be calculated from the wavelength of GWs. As an all-sky monitor, LISA will detect the dynamic cosmos using GWs as new and unique messengers and thus unfold the mysteries of the universe and gravity [10].

4.2.3. Pulsar Timing Arrays(PTAs). PTAs, made up of an array of millisecond pulsars, probe the GW from 10^{-9} to 10^{-6}Hz, and measures changes in the time when radio frequency pulses arrive at the Earth [5]. Currently, there are three major PTA cooperation groups in the world, namely North American's NANOGravi, the European PTA, and Australia's Parkes PTA. They collaborate with each other and constitute the International PTA (IPTA). China's 500-m FAST telescope and South Africa's Meer KAT telescopes have also been commissioned to join the existing PTAs [5].

4.2.4. Cosmic microwave background (CMB) polarization. The Big Bang left primordial GWs whose lowest frequencies (down to approximately 10^{-18} Hz) cannot be detected by LIGO, LISA or PTAs. Electromagnetic measurements of the CMB polarization may disclose the remnant primordial GWs [5].

4.3. Future Efforts of GW Detection

In the 2030s, the third generation(3G) ground GW detectors, like Einstein Telescope in Europe and Cosmic Explorer in the United States, can potentially detect numerous compact binary mergers and multi-messenger sources. The current LIGO observatories will be upgraded to LIGO Voyager to test the technologies for Einstein Telescope and Cosmic Explorer, and be much more sensitive than the current detectors. Space detector LISA will observe much lower frequency GWs [12]. PTAs will be further developed to be more sensitive.

4.4. Significance of GW Detection

The detection of GWs will be one of the biggest breakthroughs in physics in the past 100 years. As mentioned earlier, several other major verifications of GR, like Mercury's perihelion precession, gravitational red shift, radar echo time delay and black holes, have long been observed or proven, so the verification of GWs is the last "puzzle" of theory of GR [4].

The discovery of GWs is comparable to the discovery of electromagnetic waves. The proof of electromagnetic induction by Faraday in 1831 and the establishment of electromagnetism by Maxwell in the 1860s ushered in the era of electromagnetic wave communication. The detection of GWs in the spatiotemporal background will deepen people's understanding of the universe, and scientific research will enter the era of gravitational wave astronomy [12].

Gravitational wave communication can also help human beings to communicate with distant universes. Due to the interference of atmospheric plasma, solar wind, and galactic charge, the transmission distance of electromagnetic signals is limited. GWs are not blocked by the charges distributed throughout the universe. Human beings may use gravitational wave communication technology for interstellar communication and explore the vast universe.

5. Conclusion

Einstein raised the theory of special relativity on the shoulders of Newtonian mechanics, the electromagnetic theory and Lorentz transformations. However, this theory neglected the effect of gravity, and thus should be extended. Starting from the principle of equivalence, GR extends the classical Newton's law and special relativity theory. According to Einstein field equations, gravity is a curvature of spacetime that correlates with the energy and momentum of matter and radiation within it. Einstein thus predicted the existence of GWs, which spurred the scientists to detect the GWs. The landmarking direct detection of gravitational wave in 2015 and subsequent detections not only verified GR but also marked a transition of human society from electromagnetic wave era to gravitational wave era. GWs make it possible for people to test theories which describe the early stages of the universe, and thus triggered more ambitious efforts of developing ground- and space-based observatories and PTAs. With more joint international efforts and increasingly advanced facilities of detection, the new

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opportunities provided by GW astronomy may yield results that will change the nature of physics, and tackle some most urgent problems in physics, astrophysics, and cosmology.

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